MICROWAVE INSTRUMENT FOR THE ROSETTA ORBITER (MIRO)

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INTRODUCTION

The observed abundances of a large number of volatile molecules in comets supports the idea that comets were formed at very cold temperatures and at large heliocentric distances. Aside from thermal perturbations which may have occurred when comets were transferred from their place of origin (i.e. Kuiper belt, Oort Cloud, interstellar medium) to Jupiter family trajectories and the periodic heating which occurs when comets make their closest approaches to the sun, comets have been largely preserved at low temperatures since their formation. Comets are believed to be among the most primitive bodies in the solar system (i.e. Yamamoto, 1991, Mumma et al., 1993). Studies of comets and perhaps asteroids as well, offer the possibility of understanding the conditions that existed in the primitive solar nebula and the evolutionary path which led to the present solar system.

Prior to the 1960's, comets were investigated primarily using visible wavelength observations. Becklin and Westphal (1966) achieved the first infrared detection of a comet (Comet Ikeya-Seki (1965f)) in the wavelength range 1.65-10 μm. The first widely accepted radio detection of a comet is that of the 18-cm OH transitions in Comet Kohoutek (1973) XII (Biraud et al. 1974; Turner, 1974). Crovisier and Schloerb (1991) provide a history of comet observations at radio wavelengths; they also discuss the role of radio observations in studying all major comet components: the nucleus, the dust, the neutral gas, and the plasma. The roles of both continuum and spectroscopic observations are discussed. They emphasize that the rotational transitions of most cosmically important molecular species fall in this spectral region. The MIRO investigation builds on the work discussed by Crovisier and Schloerb, Huebner (1970), and others.

The investigation, Microwave Instrument for the Rosetta Orbiter (MIRO), addresses the nature of the cometary nucleus, outgassing from the nucleus and development of the coma as strongly interrelated aspects of cometary physics. During the flybys of the asteroids Otawara and Siwa, the MIRO instrument will measure the near surface temperature of these asteroids and search for outgassing activity in an effort to understand better the relationship between comets and asteroids. MIRO is configured to measure both broadband continuum brightness temperatures and very narrow spectral lines of a few key molecules known to be present in cometary coma. Center-band operating frequencies are near 190 GHz (1.6 mm) and 562 GHz (0.5 mm). Spatial resolution of the instrument operating in the submillimeter band is approximately 5 m at a distance of 2 km from the nucleus. The MIRO spectrometer is tuned to measure four volatile species - H_2O, CO, CH_3OH, and NH_3 and the isotopes of water —$H_2{}^{17}O$ and $H_2{}^{18}O$. These four species have all been measured to be present in comets. The spectral resolution is sufficient to observe individual, thermally broadened line shapes at all temperatures down to approximately 10 K. The MIRO experiment will use these species as probes of the physical conditions within the nucleus and coma. The basic quantities measured by MIRO are surface temperature, and gas abundance, velocity, and temperature of each species, along with their spatial and temporal variability. This information will be used to infer coma structure and outgassing processes, including the nature of the nucleus/coma interface. MIRO is highly complementary to the other experiments on the ROSETTA orbiter and lander. A summary of key Performance Parameters of the MIRO instrument is provided in Table 1.

MIRO will sense the subsurface temperature of the cometary nucleus to a depth of one centimeter or more using the continuum channels at millimeter and submillimeter wavelengths. Model studies will relate these measurements to electrical and thermal properties of the nucleus, and address issues connected to the sublimation of ices, ice and dust mantle thickness, and the formation of gas and dust jets. The global nature of these measurements will allow in situ lander data to be extrapolated globally, while the long duration of the mission will provide the opportunity to follow the time variability of surface temperatures and gas production. Models of the thermal emission from comets are very crude at this time because the available data does not strongly constrain the models; MIRO will offer the first opportunity to gather subsurface temperature data that can be used to constrain and test thermal models. The continuum channel measurements provided by the MIRO instrument will be highly complementary to the IR mapping observations from the orbiter. Both sets of observations will have similar spatial resolution but will refer to different depths beneath the solid surfaces.

The MIRO investigation was conceived and designed functionally by an investigation team (Table 2) consisting of 19 scientists from 6 different institutions, and a MIRO project office, located at JPL.

TABLE 2
MIRO SCIENCE TEAM MEMBERS

Jet Propulsion Laboratory

M. Allen (Co-I)	M. Hofstadter (Co-I)
M. Frerking (Co-I)	M. Janssen (Co-I)
S. Gulkis (PI)	T. Spilker (Co-I)

California Institute of Technology

	Millimeter	Submillimeter
Telescope		
Diameter	30 cm	30 cm
Beam-Size (FWHM)	22 arc min	7 arc min
Foot-Print (2 km nadir distance)	15 m	5 m
Spectral Characteristics		
Frequency	188.5-191.5 GHz	547.5-580.5 GHz
IF Bandwidth	1-1.5 GHz	5.5-16.5 GHz
Spectral Resolution		44 kHz (.023 km/s)
Individual spectral bandwidth		20 MHz (11 km/s)
Spectral Bandwidth/No. Channels		180 MHz/4096
Radiometric Characteristics		
DSB Noise Temp.	1000K	5000K
RMS Spectroscopic Senstivity (300 kHz, 2 min.)		2K
RMS Continuum Sensitivity(1 sec)	< 1 K	< 1 K
Data Collection Rate	0.23 - 2.53 kbps	

D. Muhleman (Co-I)

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G. Beaudin (Co-I)
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SCIENCE OBJECTIVES

The science objectives of the MIRO investigation are to:

1. Characterise the abundances of major volatile species and key isotope ratios in the nucleus ices.

The MIRO instrument will measure absolute abundances of key volatile species— H_2O, CO, CH_3OH, and NH_3—and quantify fundamental isotope ratios—$^{17}O/^{16}O$ and $^{18}O/^{16}O$ —in a region within several km or less from the surface of the nucleus, nearly independent of orbiter to nucleus distance.

Water and carbon monoxide are chosen for observation because they are believed to be the primary ices driving cometary activity. Methanol is important both as a common organic molecule and because it is a convenient probe of gas excitation temperature, by virtue of its many transitions. Knowledge of ammonia abundance has important implications for the excitation state of nitrogen in the solar nebula. The isotopic ratios of oxygen will be compared with those of the solar system, and molecular clouds to help identify the origin of comets. The MIRO investigation will combine measurements of the variation of outgassing rates with heliocentric distance with models of gas volatilisation and transport in the nucleus to quantify the intrinsic abundances of volatiles within the nucleus.

2. Study the processes controlling outgassing in the surface layer of the nucleus.

The MIRO experiment will measure surface outgassing rates for H^2O, CO, and other volatile species, as well as nucleus subsurface temperatures to study key processes controlling the outgassing of the comet nucleus.

The MIRO investigation will use correlated measurements of outgassing rates and nucleus thermal properties to test models of gas formation, transport, and escape from the nucleus to advance our understanding of the important processes leading to nucleus devolatilisation.

3. Study the processes controlling the development of the inner coma.

MIRO will measure density, temperature, and kinematic velocity in the transition region close to the surface of the nucleus.

Measurements of gas density, temperature, and flow field in the coma near the surface of the nucleus will be used to test models of the important radiative and dynamical processes in the inner coma, and thus improve our understanding of the causes of observed gas and dust structures. The high spectral resolution and sensitivity will provide a unique capability to observe Doppler-broadened spectral lines at very low temperatures.

4. Globally characterise the nucleus subsurface to depths of a few centimeters or more.

The MIRO instrument will map the nucleus and determine the subsurface temperature distribution to depths of a centimeter or more, depending on the absorption properties of the nucleus. Morphological features on scales as small as 5 m will be identified and correlated with regions of outgassing.

The combination of global outgassing and temperature observations from MIRO and in situ measurements from the Rosetta lander will provide important insights into the origins of outgassing regions and of the thermal inertia of subsurface materials in the nucleus.

5. Search for low levels of gas in the asteroid environment.

The MIRO instrument will search for low levels of gas in the vicinity of asteroids Otawara and Siwa (or others) and measure subsurface temperatures to provide information on the presence of water ice. The temperature measurements will be used to infer near surface thermal characteristics and the presence or absence of a regolith.

SCIENCE REQUIREMENTS

Continuum Requirements

Spatial Resolution: The spatial (and angular) resolution of MIRO is set by the requirement to characterize morphological features on the nucleus surface including the venting of gas. The spatial resolution (defined as the spatial distance between the half-power beam width at a specified distance) on the nucleus from a distance of 10 km is set to be 25 and 75 m respectively at 562 GHz and 188 GHz. This resolution is required to complement the IR mapping resolution.

In order to minimise the emission which enters the receivers from the near and distant sidelobes of the beam pattern, we have set the requirement for less than 10% of the signal to arise from outside the first nulls of the beam pattern, with a goal of less than 5 %.

Mapping Capability: The mapping requirement is that MIRO will be turned on during the NADIR looking observation modes. A goal is to be able to carry out off nadir mapping as well. It is desired that MIRO map the brightness temperatures of the nucleus in each of the continuum channels, over the entire nucleus, over a full range of solar phase angles, and throughout the duration of the mission.

Mapping Rate: The MIRO instrument must have the capability to map the nucleus in a time short compared to either the orbiter period around the nucleus or the nuclear rotation period. To enable this mapping, MIRO will have the capability to map the nucleus at the rate of at least 1 pixel/sec at 562 GHz. The MIRO instrument must have the capability to record data from the continuum channels at least once per second. At 10 km from the nucleus, this allows the nucleus to be mapped at the 562 GHz spatial resolution in about 2 hr, significantly less than the orbiter period which at this distance is at least two days, and the expected rotational period of the nucleus which is near 6 hours.

Relative Sensitivity Requirement: The relative measurement uncertainty of brightness temperature shall be 1 K/pixel in 1 second at both frequencies. This uncertainty is expected to be dominated by the receiver drift (changes in the receiver gain) rather than by the thermal noise in the receiver. The receiver thermal noise will be much less than the drift "noise" in the continuum channels.

Absolute Sensitivity Requirement: The absolute uncertainty of any measurement of brightness temperature shall be 3 K in 1 second after calibration.

Spectral coverage: Continuum measurements require 2 widely spaced channels centered near 190 GHz and 562 GHz. A wavelength ratio of slightly greater than two allows the thermal gradient in nucleus to be measured. Exact frequency requirements of the instrument are set by spectroscopic requirements rather than by the continuum measurements.

Spectral resolution: Bandwidths should be sufficiently broad to allow sensitivity requirements to be achieved. The noise equivalent bandwidth should be greater than 500 MHz.

Spectral accuracy and knowledge: Center frequency accuracy and knowledge should be less than 20 MHz. Note: Spectroscopic requirements are very much greater.

Radiometric calibration: Pre-launch radiometric calibration curves should be obtained over the operating temperature range. In-flight calibration capability should be provided to measure radiometric calibration, instrument gain, and baseline drifts.

Spectroscopic Requirements

Spectral Coverage: The total spectrometer bandwidth must be sufficient to include the ~8 molecular line transitions from 6 molecules seen in the 562 GHz receiver, allowing for gas Doppler velocity shifts and spectral line broadening. The list of lines and their frequencies are given in Table 3. Doppler shifts are expected to be very small for cometary observations (less than 2 km/s or 4 MHz), but much larger (17 km/sec (32 Mhz) for SIWA) for the asteroids and planetary flybys and for possible calibration related observations of astrophysical sources

Species	Frequency(GHz)
H_2O	556.936
$H_2{}^{17}O$	552.021
$H_2{}^{18}O$	547.676
CO	576.268
NH_3	572.498
CH_3OH	553.146
CH_3OH	568.566
CH_3OH	579.151

Table 3: Eight molecular lines and transition frequencies observed by MIRO.

Spectral resolution: MIRO must have the capability to measure the line profile of individual spectral lines, thereby allowing both line widths and Doppler velocities to be measured. The goal is to be able to measure line widths down to a temperature of 10 K and Doppler velocities of less than 12 m/s. To achieve this requirement, the spectral resolution must be sufficient to observe individual thermally broadened spectral lines. The Doppler (thermally broadened) full width at half maximum ($\Delta\nu_d$) is given by

$$\Delta\nu_d = \frac{\nu}{c}\,(2\,k\,T\ln(2)/m)^{0.5} = 0.356\,\nu\,\sqrt{T/M}\;10^{-6}\ \text{Hz}$$

where m is molecular mass, M is the molecular weight, T is the gas temperature, and v is the frequency in Hz. The narrowest line width is expected for the 553.146 GHz transition of methanol (CH_3OH). The line width for this transition at a temperature of 10 K is 110 kHz. The line width for water is slightly broader, 148 kHz. The MIRO spectrometer has a resolution of 44 kHz. The capability to resolve these very narrow line widths is a unique feature of the MIRO instrumentation.

Spectral accuracy and knowledge: Center frequency accuracy and knowledge should be less than (1/10) x spectral resolution.

Spatial Resolution: The spatial resolution at 10 km from the nucleus shall be 25 and 75 m respectively, at 562 GHz and 190 GHz. This resolution is required to search for small gas vents and surface features, and to complement the IR mapping resolution. In the mapping mode, it is important to minimise the surface emission, which enters the receivers from the near and distant sidelobes of the telescope. The requirement is that less than 10% of the total signal arise from outside the first nulls of the beam pattern. The goal is to reduce this to 5%. In the limb sounding mode, we want to minimise the radiation, which enters the receivers outside of the main beam, and particularly from the nucleus.

Mapping and Limb Sounding Capability: MIRO will take spectroscopic measurements in both a down looking (near nadir) mapping mode and in a limb sounder mode. In the spectroscopic mode, integration times up to 10 minutes in duration are planned to achieve high sensitivity. The spatial resolution for long integration will be degraded relative to the continuum mode.

Limb Sounding Range, Step Size, and Integration Time: A goal is to acquire limb sounding spectra over a wide range of viewing directions. Starting at the limb of the nucleus as seen from the spacecraft, the desire is to view the coma at successively larger altitudes. Step sizes measured from the direction of the limb are typically 10 degrees and integration times are up to 10 minutes. Integration times, step sizes, and range can be arranged to fit the spacecraft capabilities.

Relative Sensitivity Requirement: The MIRO spectroscopic sensitivity will allow measurements of water vapour having a surface flux density of 1.2×10^{12} molecules/cm^2sec. Assuming a radius of 700m, the detectable production rate is less than 1×10^{23} molecules/sec. The MIRO spectroscopic sensitivity is sufficient to measure the outgassing of water at heliospheric distances greater than 3.25 AU. Carbon monoxide can be measured when the comet is within 2 AU of the sun. The MIRO spectroscopic sensitivity for 300 kHz resolution shall be dT = 2 K rms in 120 seconds (single sideband).

Absolute Sensitivity Requirement: The absolute uncertainty of any measurement of brightness temperature shall be 3 K in 10 minutes.

INSTRUMENT REQUIREMENTS

The science requirements discussed above translate into the instrument requirements shown in Table 4.

ITEM	PROPERTY	MILLIMETER	SUBMILLIMETER
Field of View	Half Power Beam Width	< 22 arc min	< 8 arc min
	Percent Power in main beam	> 90%	>90%
	Near sidelobe levels	< 30 dB	< 30 dB
	All sidelobe levels	< 30 dB	< 30 dB
	Edge taper on primary mirror	> 20 dB	> 20 dB
	Surface Accuracy of Primary	< 10 microns	< 10 microns
Spectral GHz	Frequency Band	186.7-189.7 GHz	546.9-579.2
	Bandwidth/line	N/A	20 MHz
	Spectral Resolution	N/A	< 100 kHz
•	Accuracy	N/A	10 kHz
Radiometric Sensitivity			
	Spectroscopic	N/A	2K(120s, 300kHz, SSB)
	Continuum	1 K (1 s)	1 K (1 s)

Table 4 : MIRO Instruments Requirements

HARDWARE DESCRIPTION

The MIRO instrument consists of two heterodyne radiometers, one operating at millimeter wavelengths (190 GHz, ~1.6 mm) and one operating at submillimeter wavelengths (562 GHz, ~0.5 mm). Figure 1 provides a schematic configuration of the MIRO instrument. The millimeter and submillimeter radiometers are both configured with a broadband continuum detector for the determination of the brightness temperature of the comet nucleus and the target asteroids. The submillimeter receiver is also configured as a very high resolution spectrometer for observations of the eight molecular transitions shown in Table 2.

The instrument is comprised of four separate physical modules, interconnected with a wiring harness cable. The <u>Sensor Unit</u> includes the telescope, baseplate, and optical bench. The Sensor Unit is physically mounted on the spacecraft payload plane using the baseplate as the interface with the spacecraft. The MIRO telescope boresight direction is aligned to the ROSETTA payload line of sight. The optical bench is mounted to the underside of the baseplate, under the telescope and inside the spacecraft. The millimeter- and submillimeter-wave receiver front ends, the calibration mechanism, and the quasi-optics for coupling the telescope to the receivers are mounted on the optical bench. A <u>Sensor Backend Electronics Unit</u> contains the intermediate frequency processor (IFP), the phase lock loop, and frequency sources. It is mounted next to a louvered radiator internal to the spacecraft. The Electronics Unit contains the Chirp Transform Spectrometer (CTS), the instrument computer, and the power conditioning circuits. The Ultra Stable Oscillator Unit, described below, is a self contained thermally controlled oscillator.

Optics

Figure 2 shows the optical bench assembly with the positions of the beam waveguide mirrors shown in their correct relative orientation. Light enters the MIRO instrument through an offset parabolic primary mirror of 30 cm diameter and focal length of 32 cm. The offset parabolic primary eliminates blockage of the primary by the secondary. A Cassegrain (hyperboloid subreflector) design is used to minimise volume of the telescope and provides very low sidelobes. Light from the primary is reflected to the hyperboloid subreflector where it is directed inside the spacecraft to the elliptical turning mirror on the optical bench. The turning mirror directs a Gaussian shaped beam toward the wire grid Diplexer, which reflects the submillimeter beam to the submillimeter matching mirror. The Diplexer transmits the millimeter beam to the matching mirror. The two matching mirrors direct the millimeter and submillimeter beams respectively to the feed horns of the two receivers. Viewed as a transmitting system, the two feed horns illuminate the primary with a Gaussian shaped pattern with > 20 dB edge taper, resulting in < 30 dB sidelobes for the primary beam pattern.

The accuracy of the primary surface is 10 μ RMS corresponding to less than $\lambda/50$ at 0.535 mm. Combining the effects of the illumination, surface error, and reflectivity losses, the telescope has an aperture efficiency of greater than 0.7 and a main beam efficiency of greater than 0.93 at both frequencies.

The end-to-end optical system is designed to minimise alignment sensitivity to the large temperature range the telescope will experience during the course of the mission. The telescope is fully exposed to the space environment. It is expected to operate from approximately ~100 K at the comet rendezvous to a temperature of ~300 K at perihelion. A thermal isolator (G10 fiberglass) is placed between the telescope and the mounting to the baseplate. To maximise performance over this large temperature range, the telescope is fabricated with aluminium so that it scales with temperature to maintain a sharp focus. The beam is nearly parallel at the telescope/optical bench interface minimising misalignment along the optical path. Lateral misalignments are minimised by symmetrical design in one axis and fixing the telescope mount near the beam axis from the subreflector to the turning mirror..

Heterodyne Receivers

Millimeter Wave Heterodyne Front End: The millimeter wave receiver is configured as a total power radiometer. The principal components of the radiometer are the feed horn, mixer, low-noise amplifier, local oscillator (LO) and detector. A block diagram of the system is shown in Figure 3. The mixer, designed as a subharmonic mixer, uses an LO frequency at half the signal frequency (95 GHz) to downconvert the signal frequency to the frequency range 1-1. 5 GHz. The mixer uses a planar diode. A Gunn oscillator provides the LO signal. After amplification, the signal is fed to the Intermediate Frequency processor where it is filtered and detected.

Submillimeter Wave Heterodyne Front End: The submillimeter wave receiver is designed to operate simultaneously both as a radiometer for continuum measurements and as a spectroscopic receiver. The principal components of the submillimeter wave front end are the feed horn, mixer, low-noise amplifier, and local oscillator (LO). A block diagram of the submillimeter wave receiver is shown in Figure 4. The mixer, designed as a subharmonic mixer, uses an LO frequency at half the signal frequency (282 GHz) to downconvert the signal frequency to the frequency range 5.5-16.5 GHz. The mixer uses a planar diode. A Gunn oscillator provides the LO signal. The Gunn oscillator is designed to rapidly shift its frequency by +- 5 MHz thereby causing the observed spectral lines to shift their positions slightly within the passband. This frequency switching technique helps to remove any baseline variations that may be present and gain variations in the receiver. Following amplification, the signal is fed to the Intermediate Frequency Processor.

Intermediate Frequency Processor

The Intermediate Frequency Processor (IFP) processes the IF signal from both the millimeter and submillimeter front ends. The output intermediate frequencies (IF) from both heterodyne receivers are connected directly to the input of the IFP as shown in Figures 3 and 4. A block diagram of the IFP is shown in Figure 5.

The IF signal from the millimeter receiver is filtered and detected in the IFP, but no further frequency translation is performed. The IF signal from the submillimeter receiver undergoes much more signal processing in the IFP. The additional signal processing is required to translate the 8 molecular transitions in Table 3, into the appropriate frequency range for the Chirp Tranform spectrometer.

The submillimeter signal is first fed to a power divider in the IFP which divides the power into a continuum band and a spectroscopic band. The continuum band is filtered and detected as is done for the millimeter receiver. The spectroscopic band contains the 8 molecular transitions shown in Table 3. Nine mixers (M1 through M9) and three local oscillator sources (2.182 GHz, 7.147 GHz, and 7.728 GHz) are used to translate the spectral line frequencies to appropriate CTS input frequencies. Table 5 gives the frequency of the spectral line at each stage of the conversion process. The column labelled "IF1" shows the lines positions immediately following the first mixing process. The column labelled "Output" shows the line frequency as it leaves the IFP and enters the CTS spectrometer.

Approximately 20 MHz wide filters are used in the IFP to reduce overlap between spectral lines and to reduce out-of-band noise. These filters establish the maximum permissible Doppler shift for an individual spectral line. The filters will allow observations over Doppler shifts of ±5.4 km/sec or ± 8 km/sec using frequency switching. This will allow short spectral observations of the asteroids near closest approach, and calibration measurements of low velocity molecular clouds.

		IF 1	IF 2	IF 3	IF 4	IF 5	IF 6	IF 7	IF 8	IF 9	Output
Lines	RF (MHz)		M1 out	M2 out	M3 out	M4 out	M5 out	M6 out	M7 out	M3 out	to
		(LO1)	(2xLO2)	(LO4)	(L04)	(LO3)	(LO2)	(LO3)	(2xLO2)	(LO4)	CTS
$H_2{}^{18}O$	547677	15136	-	-	-	7989	5807	1340	-	-	1340
$H_2{}^{17}O$	552021	10792	6428	-	1300	-	-	-	-	-	1300
CH_3OH	553146	9667	14031	6303	1425	-	-	-	-	-	1425
$H_2{}^{16}O$	556936	5877	-	-	-	1270	-	-	-	-	1270
CH_3OH	568566	5753	1389	-	-	-	-	-	-	-	1389
NH_3	572498	9685	14049	6321	1407	-	-	-	-	-	1407
CO	576268	13455	9091	1363	-	-	-	-	-	-	1363
CH_3OH	579151	16338	-	-	-	9191	-	2044	6408	1320	1320

Table 5: IF frequencies for the submillimeter-wave receiver. Mixer numbers (M1-M9) refer to mixer labels given in Figure 5.

Spectrometer

The spectrometer on MIRO measures the power spectrum of the output band of frequencies from the IFP. The type of spectrometer used on MIRO is known as a Chirp Transform Spectrometer (CTS). Related spectrometer types are the Chirp-Z Transform Receiver, the Compressive Receiver, and the Microscan Receiver which have been used primarily for the detection of pulsed radars. The CTS operates on principles that have been known for over thirty years (Klauder et al., 1960, Jack et al., 1980) but rarely used for the detection of random noise signals encountered in radio astronomical applications. The principal advantage of the spaceborne CTS over other spectrometer types is that it allows very high spectral resolution over a wide range of frequencies for modest mass, volume, power and cost budgets.

The Fourier Transform, written in the form

$$F(2\pi\mu t) = \exp(-j\pi\mu t^2)\int_{-\infty}^{\infty}\left[f(\tau)\exp(-j\pi\mu\tau^2)\right]\exp\left[j\pi\mu(t-\tau)^2\right]d\tau$$

where

$\omega = 2\pi\mu t$, and

$2t\tau = t^2 + \tau^2 - (t-\tau)^2$

is called a Chirp Transform. The complex square product of $F(2 \pi \mu t)$ is the power spectrum of $f(\tau)$. The Chirp Transform equation provides the basis for the operation of the MIRO CTS. The three exponential terms in this equation having a squared frequency dependence are called "chirp" waveforms and μ is the chirp rate. The Chirp Transform can be seen to be the equivalent of multiplication of the original signal $f(\tau)$ by a complex chirp, $\exp(-j \pi \mu \tau^2)$, followed by a convolution with a second chirp, $\exp(-j \pi \mu (t - \tau)^2)$, integration, and finally multiplication of the integral by a third chirp. The final multiplication by the third chirp affects the phase of the transform but is not necessary for the power spectrum ($F \times F^*$). This operation is omitted from the MIRO spectrometer.

The MIRO CTS consists of an analog section which computes $F(2 \pi \mu t) \exp(j \pi \mu t^2)$ and a digital integrator processor section which allows the power spectrum to be accumulated. The Chirp Transform is implemented using dispersive large-Time-Bandwidth Surface Acoustic Wave (SAW) filters. The large-Time-Bandwidth product of SAW filters is a critical parameter which makes them useful in the Chirp Transform application. In the MIRO CTS application, the Time-Bandwidth product is ~ 4050. Figure 6 shows the configuration used for the MIRO experiment. Two chirp transform operations are carried out simultaneously in the MIRO CTS. For each transform operation, a chirp signal is generated by inserting a narrow band pulse into a reflective array compressor (RAC) filter with 450-MHz center frequency, 180-MHz bandwidth, and 22.1-μs dispersion time. The resultant waveform has a negative frequency slope. This process is carried out in the EXP1 (expander 1) unit in Figure 6. Following amplification, the chirp is further dispersed by a second RAC filter in EXP 2. The twice expanded chirp is amplified and frequency doubled. The output signal from the tandem expanders is a chirp centered around 900 MHz with 360-MHz bandwidth and 44-μs dispersion time.

The input signal from the IFP is multiplied by the tandem expander output chirp. The mixing operation reverses the chirp slope in the lower sideband. The lower sideband difference frequency is fed to a third RAC filter (of the same type used in the expander) called a compressor. The compressor unit has an input center frequency of 450 MHz and a bandwidth of 180 MHz (the input bandwidth of the CTS). The second convolution is performed in the compressor.

The output from both compressors are mixed with a 550 MHz signal in phase quadrature to provide the real and imaginary components of the amplitude. Following 8-bit digitization, a square law look up table provides an estimate of the power in each resolution time interval. The complete frequency range is swept at a rate of 44751 per second (each 22.346 -μs). Within a 22.346-μs interval, 4096 digitised channels are stored into an acquisition memory. The next spectrum is available after 22.346 μs and added channel by channel to the stored spectrum. The memory read out interval is programmable between 80 μs and 20 s. The spectrometer output is a digitised power spectrum supplied to the Command and Data Handling System. The spectrum resolution is ~ 45kHz.

Reference Oscillator

The absolute frequency of the MIRO instrument is maintained through the use of an ultra stable oscillator (USO) which provides the high accuracy frequency reference for the local oscillators. Over a mission lifetime estimated to be 15 years, the oscillator has been designed to drift by no more than 0.5 MHz at 560 GHz, a stability of approximately one part in a million. This will insure that no spectral lines will drift outside of their allocated passband of 20 MHz. The stability required to perform an integration of an individual spectral line is much higher. For this purpose we, assume that the oscillator can drift by no more than about 4 kHz(1/10 of the spectral resolution of the CTS) over 10 minutes. This leads to a stability requirement of approximately one part in 100 million. Our initial estimates are that the flight USO will have a stability ten times better than this requirement.

Flight Computer

The flight computer for MIRO is a radiation hardened Reduced Instruction Set Computer (RISC) System/6000 (also referred to as RS/6000). The same model computer was used on the Mars Pathfinder and Mars Surveyor Projects. The design of this computer is based on the Rios Single Chip (RSC) RISC microprocessor with implementation of the VMEbus and RS232 interfaces and it provides up to 128 Mbytes of local memory (RAM). The processor is a single chip implementation of the IBM Model 220 workstation and it is considered to be in the POWER PC architecture family.

INSTRUMENT CALIBRATION

Radiometric calibration of the MIRO instrument is obtained by observing two blackbody targets, each maintained at a different temperature. One target, the cold target, is exposed to space, while the other target is mounted inside the spacecraft at a nominal temperature of 300 K. The temperature difference between the targets will be maintained by a controllable heater on the warmer target large enough to permit accurate calibration of the receivers in a few minutes of integration time. Thermistor sensors provide accurate measurements of the calibration targets. A mechanical calibration switch positions the beam to observe the telescope, the cold target, or the hot target. This beam switch is the only moving mechanical part of the system. Typically, the continuum radiometer is switched to the calibration targets every 30 minutes to account for gain fluctuations.

During spectroscopic observations, the submillimeter wave receiver is operated in a "frequency switched" mode to eliminate residual baseline ripple. For half the integration time, the signal frequency is shifted 5 MHz above the nominal frequency, while the other half of the time it will be shifted 5 MHz below. The frequency switching occurs at a commandable interval in the range of 1 to 5 seconds, hence compensating for short-term drifts.

OPERATIONS

The MIRO instrument is configured to have six modes of operation, including a hibernation mode. Modes of operation have been designed to allow the receiver to operate over a wide range of power, depending on the power availability. Single and dual receiver continuum modes are available when power availability is low. These modes will allow the surface temperature of the target comet and asteroids to be measured. Various combinations of continuum and spectroscopic modes are available when higher powers are available. The spectroscopic modes allow sensitive measurements of the eight spectral transitions in the comet coma (and possibly the asteroids as well).

In the comet rendezvous stage of the mission, MIRO will initially turn on in continuum mode and begin nucleus sounding measurements. During the cometary and targeted mapping phases, a majority of the viewing will be in the one or two receiver/spectrometer modes to study outgassing processes, bulk composition, and coma formation. These phases will provide the highest spatial resolution for studying the nucleus. If limb sounding is feasible, it will enhance the minimum detectability of species, and allow greater resolution of the coma.

Following the mapping phase, MIRO plans to operate in the two receiver/spectrometer mode. During this phase, both nucleus and coma studies will be performed.

SENSITIVITY

The sensitivity of the MIRO instrument is ultimately set by the combination of thermal noise and gain instabilities present in the receivers. The combined sensitivity of the total power receivers on MIRO can be expressed as

$$\Delta T_{rms} = T_{sys} \sqrt{\left(\frac{1}{B\,\tau}\right) + \left(\frac{\Delta G}{G}\right)^2}$$

where T_{sys} is the system noise temperature, B is the predetection bandwidth being used, τ is the post detection integration time, and $\Delta G/G$ is a measure of the power-gain variations. Either the thermal noise or the "gain noise" dominates the sensitivity depending which term is larger. The rms noise temperature, ΔT_{rms}, needs to be compared with the received equivalent noise power temperature to determine the signal to noise ratio of any individual measurement.

Typical values of $\Delta G/G$ measured in the laboratory are approximately .0002 for both receivers, nearly independent of bandwidth. This value is likely to improve slightly after launch when the thermal environment of the instrument stabilizes. Since the continuum measurements use a large predetection bandwidth (500 MHz and 1000MHz for the millimeter and submillimeter wave receivers respectively), the "gain noise" dominates the continuum measurements for integration times longer than a few milliseconds. Noting that the double sideband noise temperatures of the millimeter and submillimeter receivers are approximately 1000 K and 5000 K respectively, the ΔT_{rms} is approximately 1 K. We assume the RMS continuum sensitivity is 1K or less in 1 second of integration time.

The spectroscopic sensitivity is dominated by thermal noise since the bandwidth of individual channels is only 44 kHz. Except for very narrow spectral lines, it will be possible to average several channels together to achieve a high sensitivity. Taking 200 kHz as a typical bandwidth, we estimate the rms sensitivity in a two minute integration time to be less than 2 K. For this calculation, we used a single sideband noise temperature of 10,000 K.

An estimate of the detection capability of the MIRO spectrometer can be obtained by computing the column density of molecules needed to produce a given line temperature. Column 3 in Table 5 shows the minimum detectable column density necessary to produce a line strength of 2 K assuming a gas temperature of 300K.

Molecule	Frequency	Minimum Column Abundance (number/cm^2)
H_2O^{16}	556.9	1×10^{13}
H_2O^{17}	552.0	1×10^{13}
H_2O^{18}	547.7	1×10^{13}
NH_3	572.5	6×10^{13}
CO	576.3	1×10^{15}
CH_3OH	553.1	1×10^{15}
CH_3OH	568.6	1×10^{15}
CH_3OH	579.1	7×10^{14}

TABLE 5: Minimum detectable column densities to produce a line strength of 2 K assuming a gas temperature of 300 K.

MASS, POWER, DATA RATE AND DATA VOLUME

Mass

The current best mass estimate, in kg, of the MIRO instrument is provided in Table 6.

Sensor Unit			6.1 kg
Telescope	1.73		
Baseplate	1.48		
Optical Bench	2.89		
Sensor Backend Electronics Unit		5.03	
Ultra Stable Oscillator Unit		1.15	
Electronics Unit			7.01
Wiring Harness			0.64

Total	19.93

Table 6 – Current best mass estimate of the MIRO instrument in kilograms. This estimate does not include mass of multi-layer insulation(MLI).

Power

Current best estimates for the required instrument power of the six operational modes of the MIRO instrument are provided in Table 7. Different observation strategies and modes are planned to keep the average utilized power to less than 43 watts for mission phases.

Mode	Average (watts)	Peak (watts)
Hibernation	2.0 W	2.0 W
Continuum, mm	16.9	23.1
Continuum, smm	19.7	25.9
Full Continuum	26.3	32.6
Spectroscopic	51.7	58.0
Full	57.3	63.6

Table 7 – Average and peak instrument power for the six different operational modes. Peak powers are encountered during calibration periods.

Data Rate and Volume

The nominal data rates for MIRO ranges from 0.23 Kbits/s for the continuum modes to 1.93 Kbits/s for the full spectroscopic mode. The peak data rate, used when high time resolution is needed, is 2.53 Kbits/s. The total accumulated data volume, from launch through the near perihelion phase is estimated to be 9.213 Gbytes.

CONCLUDING REMARKS

The MIRO instrument is a new class of instrument for planetary/cometary spacecraft. Although conceived many years ago as a potentially important instrument for cometary science, it is only recently that receiver technology has advanced to the point that such a receiver could be built within the mass, power, and sensitivity needed for this space application. A primary capability of the MIRO instrument is its capability of detecting and measuring individual, thermally broadened spectral lines of important cometary molecules.

As MIRO is presently under construction, final performance and physical parameters are not yet available. The data reported in this paper summarizes our best estimates of the MIRO instrument parameters based on completion of the STM (structural and thermal model) and partial construction of the Engineering Qualification Model (EQM).

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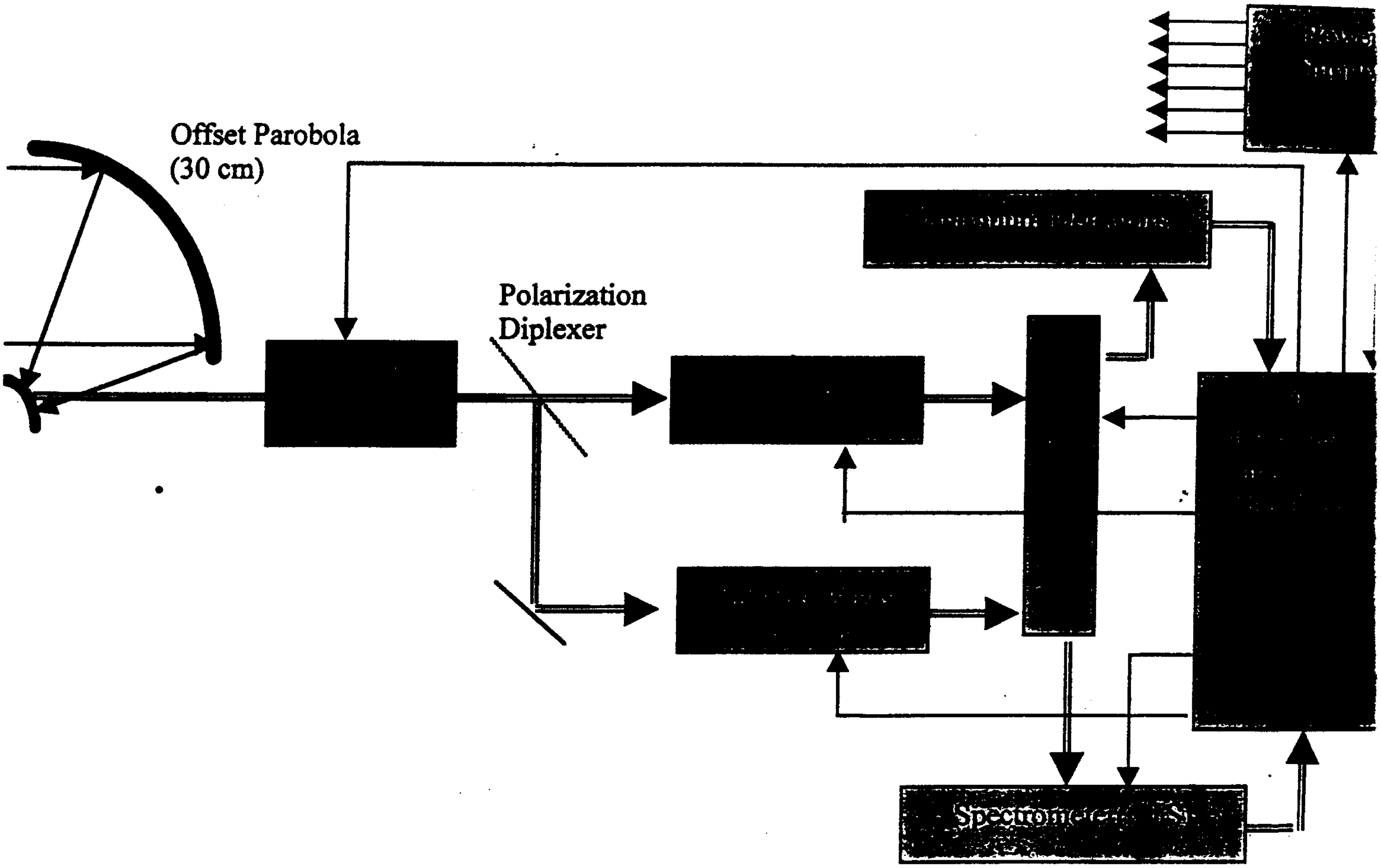
FIGURES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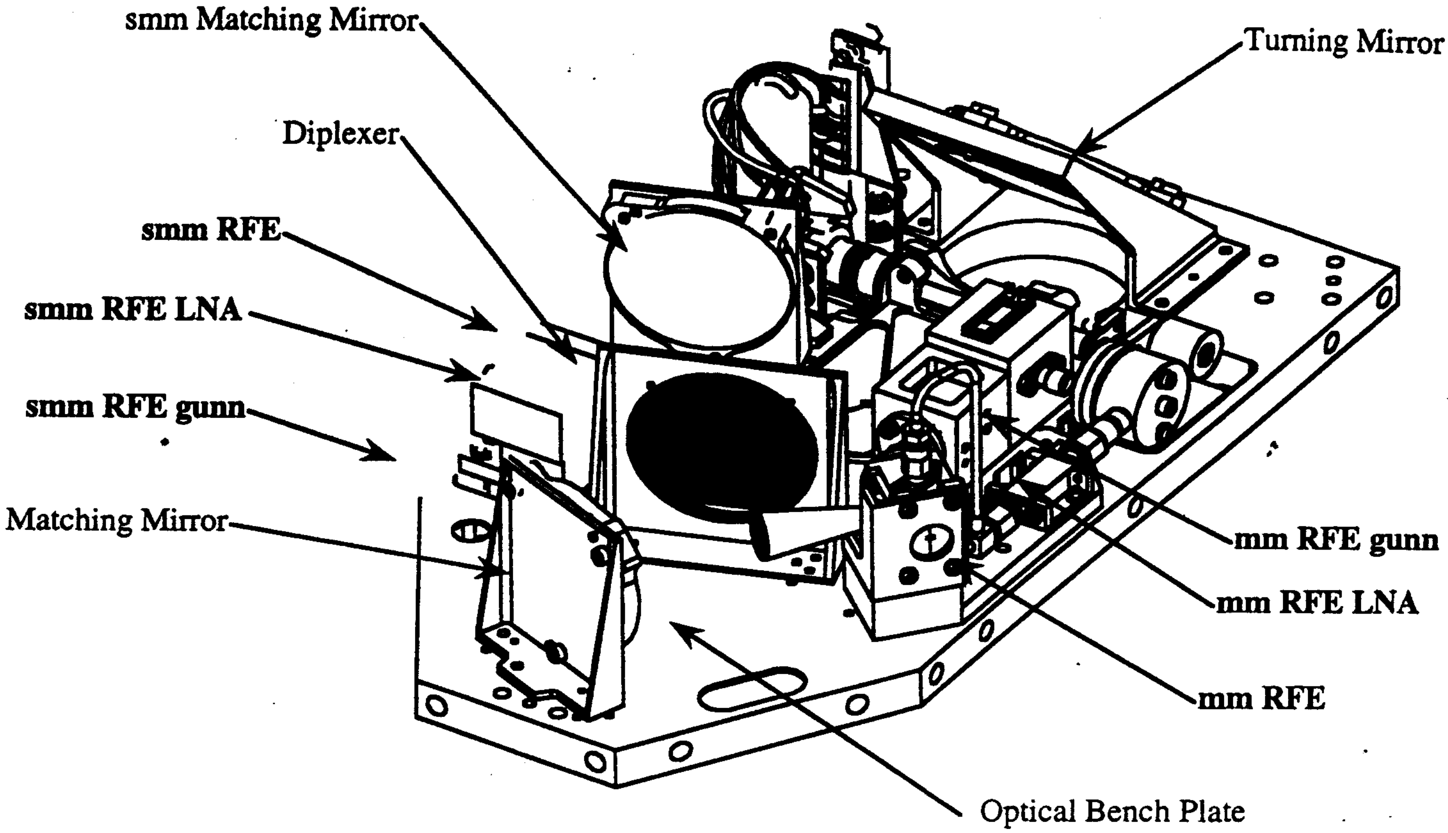
(30 cm)
Polarization
Diplexer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smm RFE LNA
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mm RFE gunn
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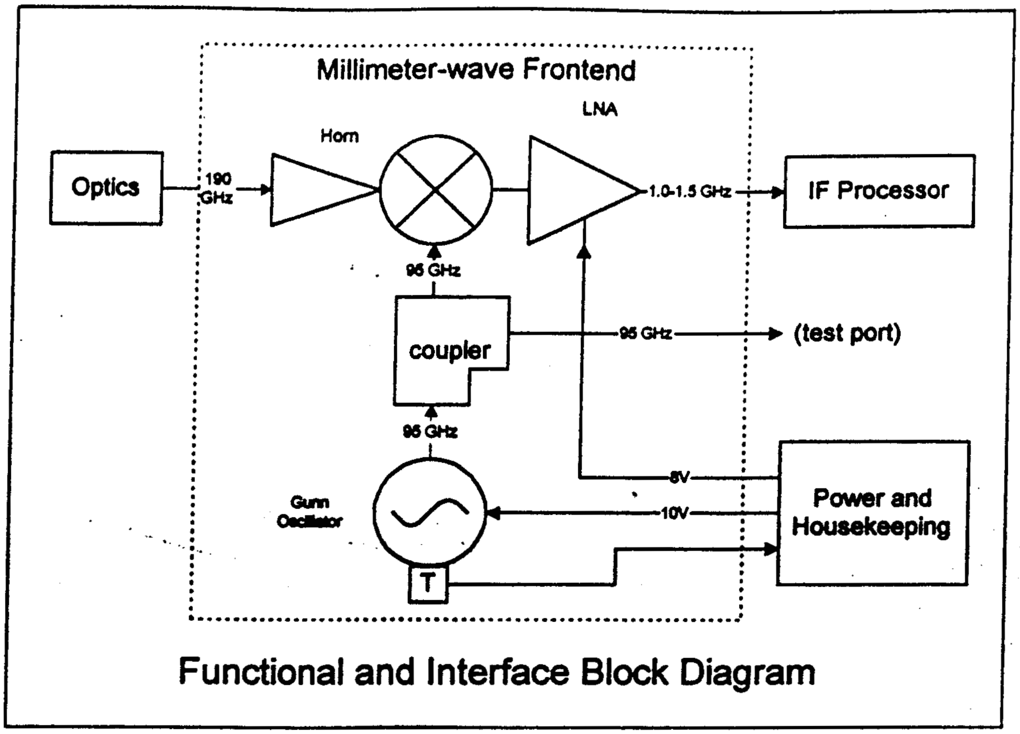


Figure 3: Schematic diagram of the millimeter-wave receiver front end

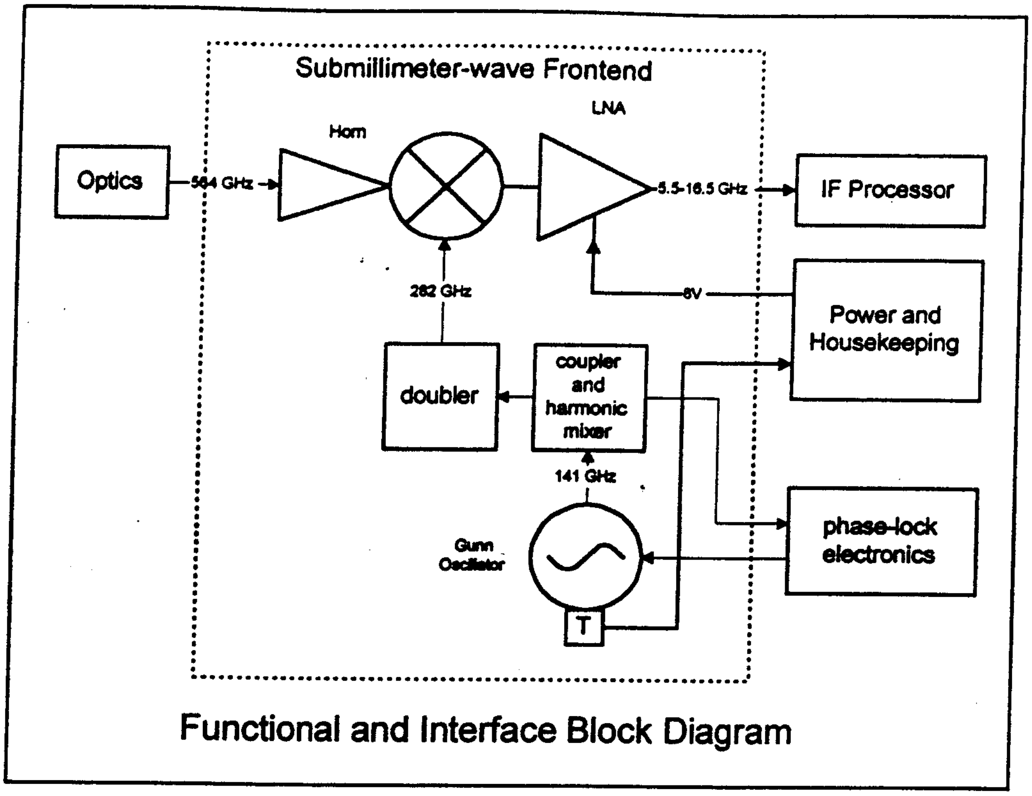
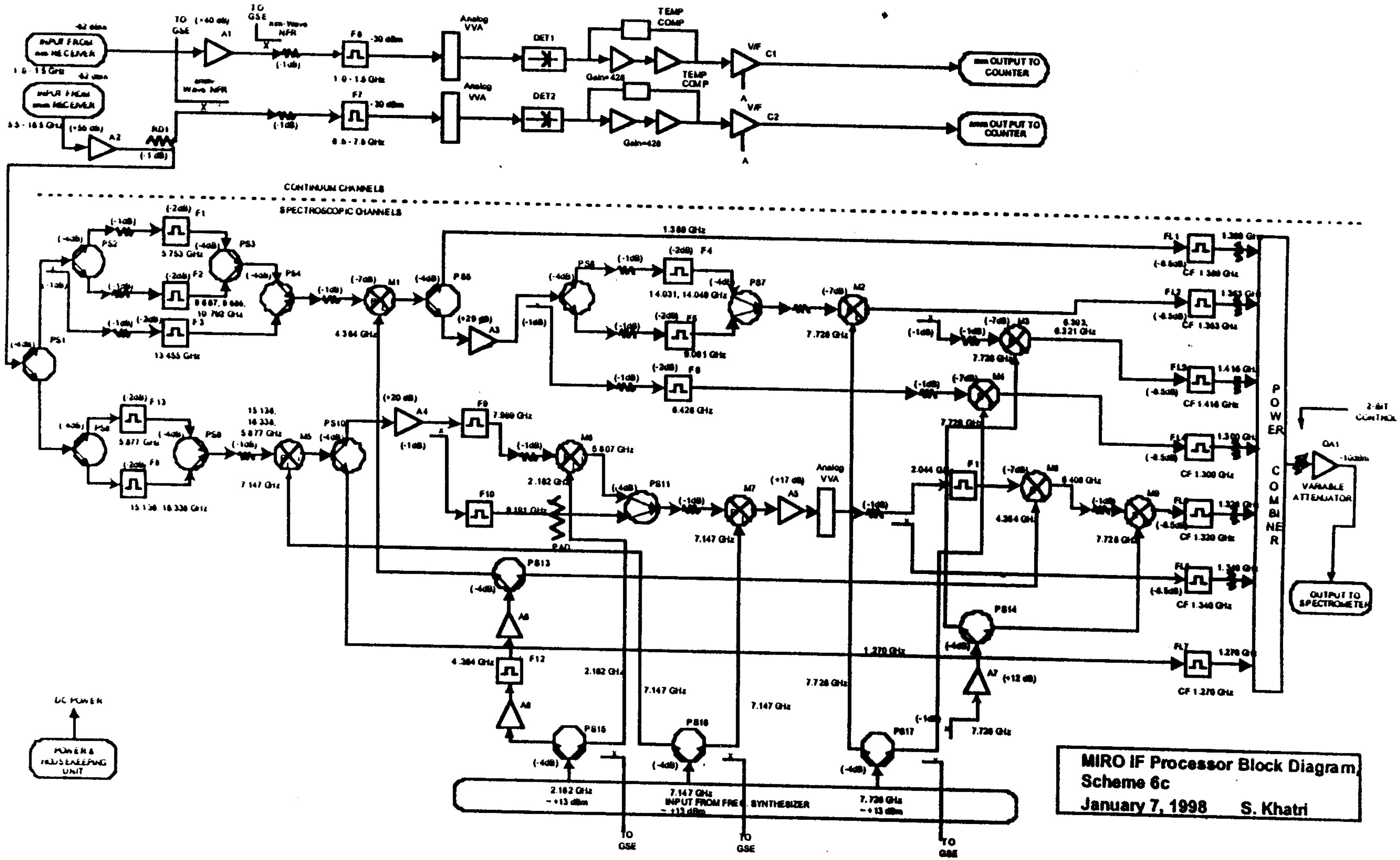


Figure 4: Schematic diagram of the submillimeter wave receiver front end


CONTINUUM CHANNELS
SPECTROSCOPIC CHANNELS
POWER COMBINER
VARIABLE ATTENUATOR
OUTPUT TO SPECTROMETER
INPUT FROM FREQ. SYNTHESIZER
POWER & HOUSEKEEPING UNIT
DC POWER
MIRO IF Processor Block Diagram,
Scheme 6c
January 7, 1998 S. Khatri

4

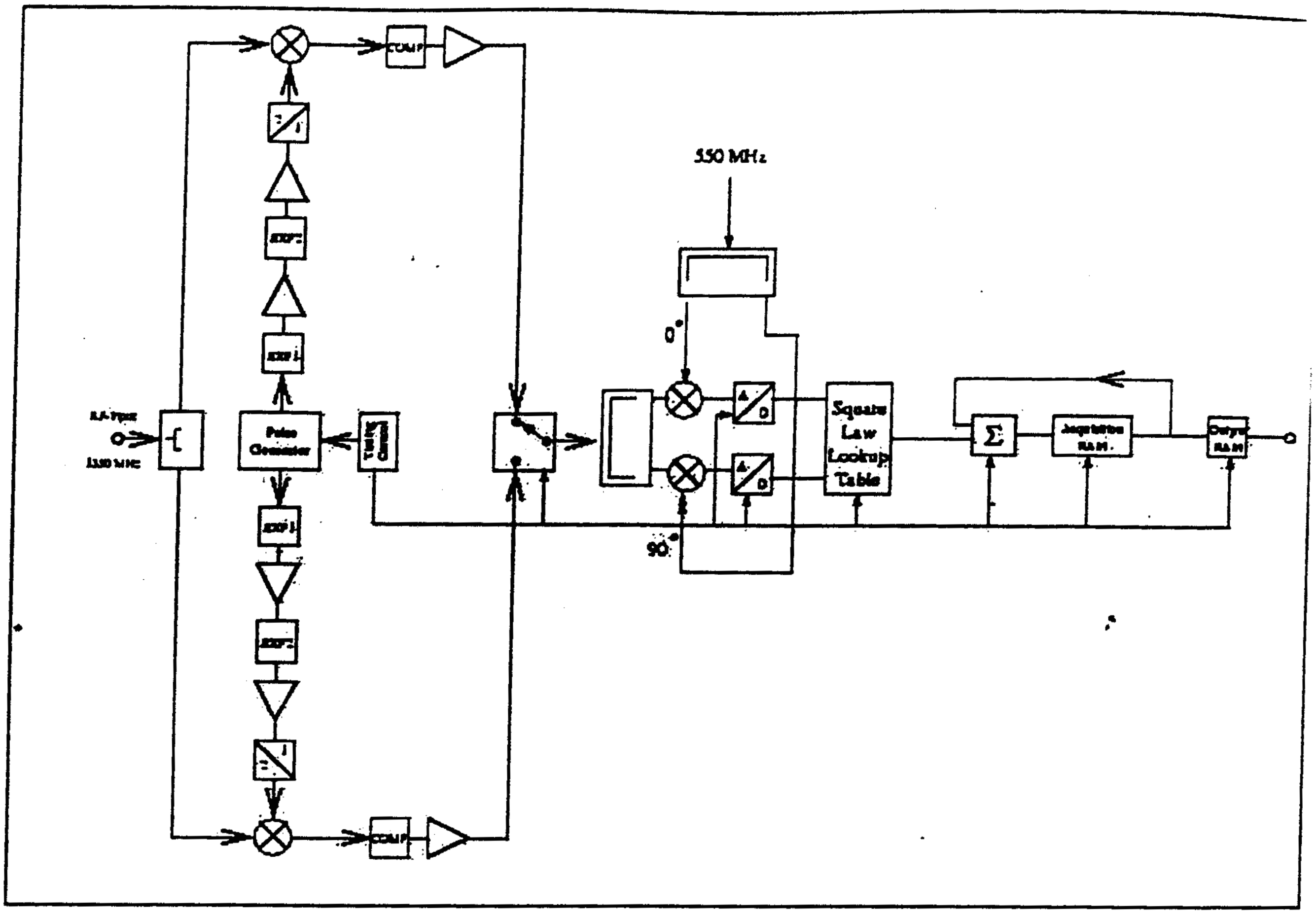


Figure 6 - Chirp transform spectrometer configuration